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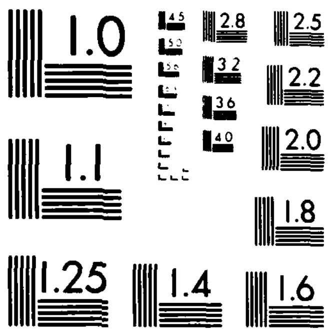

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OPTICALLY BISTABLE DEVICES USING SEMICONDUCTOR MATERIALS

Heriot-Watt University

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This report covers work conducted from February 1982 to February 1983 on the nonlinear optical properties of semiconductors using tunable (bandgap resonant) laser sources. Emphasis is on CO laser studies of InSb at 77K, but an optical parametric amplifier is constructed for future work on systems at shorter wavelengths.

The Optical Bistability and device properties of InSb have been investigated. Operation of a slice of InSb, held at 77K, pumped by a cw CO laser, as an optical AND gate, triggered by 30 ps pulses at wavelength 1.06 μm with energies of 3 nJ, is demonstrated. By using temporal separation of the trigger pulses, information on the carrier dynamics is obtained.

The design and construction of an angle tuned Optical Parametric Amplifier consisting of a lithium niobate crystal pumped by a 30 ps pulse from a Nd: YAG laser has been achieved.

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This system utilizing a grating feedback arrangement provides picosecond (pulse) tunable radiation from 1.45 to 2.1 μm. Optical absorption saturation, above the band edge of $In_{0.53}Ga_{0.47}As$ is being studied using this system.

DEPARTMENT OF PHYSICS

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Research Proposal: Optically Bistable Devices using Semiconductor Materials

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Principal Investigator: Professor S. D. Smith FRS

PART 1

1 SUMMARY

The operation of a natural reflectivity InSb bistable resonator at 77 K pumped with a cw CO laser at 1819 cm^{-1}, as a single pulse detector with a definite threshold energy (5 nJ), and as an optical AND gate is reported. The switching pulses are provided by a modelocked Nd:YAG laser, operating at 1.06 μm (9430 cm^{-1}) producing single 35 ps pulses. A unique technique is used in which two 1.06 μm, 35 ps pulses separated by a variable time delay are used to measure the photogenerated carrier lifetime. A recombination time of $\sim$ 90 ns has been measured for a cw holding intensity of $\sim$ 80 W/cm^2.

2 Introduction

Several recent reviews have been written on optical bistability and related phenomena covering both experimental and theoretical work. For a more general account of the topic the reader is referred to them[1-3]. A brief qualitative explanation of dispersive bistability is given here. This is followed by details of the construction and operation of an InSb bistable element. The switching mechanisms of this device are discussed and the concept of "external" switching introduced. Our experimental results are then presented and the implications of these results reviewed, both in terms of the non-linear refractive effects in InSb and more generally as the operation of an all-optical logic element.

It is important to note the potential significance of this work. Despite the many publications speculating on the uses of this refractive

effect in different III-V semiconductors, and other similar low power electronic non-linear refractive effects in semiconductors such as that observed in GaAs by Gibbs et al.[4], the InSb/CO laser system is the only such device which has shown bistability using a cw laser. Therefore it offers a unique opportunity to observe and study the behaviour of such a system, under various conditions, notably from the steady state to dynamic switching on picosecond timescales.

The work presented in this chapter has been the subject of two conference papers[5][6] and an Applied Physics Letter[7].

3 Dispersive Optical Bistability

The simplest dispersive optical bistable device is a Fabry-Perot resonator filled with a medium in which the refractive index is dependent on the optical field intensity.

The condition for maximum transmission in a Fabry-Perot resonator is that the length of the resonator is equal to an integral number half wavelengths of the incident light. In the non-linear case this can be written as

$$\frac{m\lambda}{2} = n(I)\ell \qquad 3.1$$

where m is an integer, ℓ is the cavity length and λ is the wavelength. The function $n(I)$ expresses the dependence of refractive index on intensity, which to first order can be taken as

$$n(I) = n_0 + n_2 I \qquad 3.2$$

If the cavity is held slightly off resonance, then by varying the incident intensity it is possibly to move towards resonance. Figure 1 shows the typical transmission characteristics of a Fabry-Perot resonator, as a function of frequency. The shape of the curve depends on the finesse of the cavity. An increase in intensity has the effect of moving this curve to the left if the refractive index reduces with intensity as is the case in InSb, under the experimental conditions used here. As the cavity moves towards resonance, a greater proportion of the incident light is allowed into the cavity, therefore the non-linear effect increases with effective positive feedback. This mechanism allows small signal gain. At higher intensities the transmission will drop again, as the cavity is moved off resonance, and at even higher intensities the next resonance will occur, and a series of steps of increasing and decreasing transmission will occur.

Figure 2 shows the input power versus output power for an InSb cavity at a wavelength and intensity for which the refractive index is intensity dependent, and the transmission steps can be seen. When the change in transmission induced by a change in incident intensity is large enough, enough intensity is allowed into the cavity to make the transmission change so rapidly that an instability can result, and the cavity can be pulled onto resonance into a stable state. A similar effect occurs as the input intensity is decreased and the device switches itself from off to on resonance. The region of input powers where two stable states exist is known as the bistable region.

A rigorous mathematical account of what is happening has proved very hard to formulate and many approaches have been used. Felber and Marburger[8]

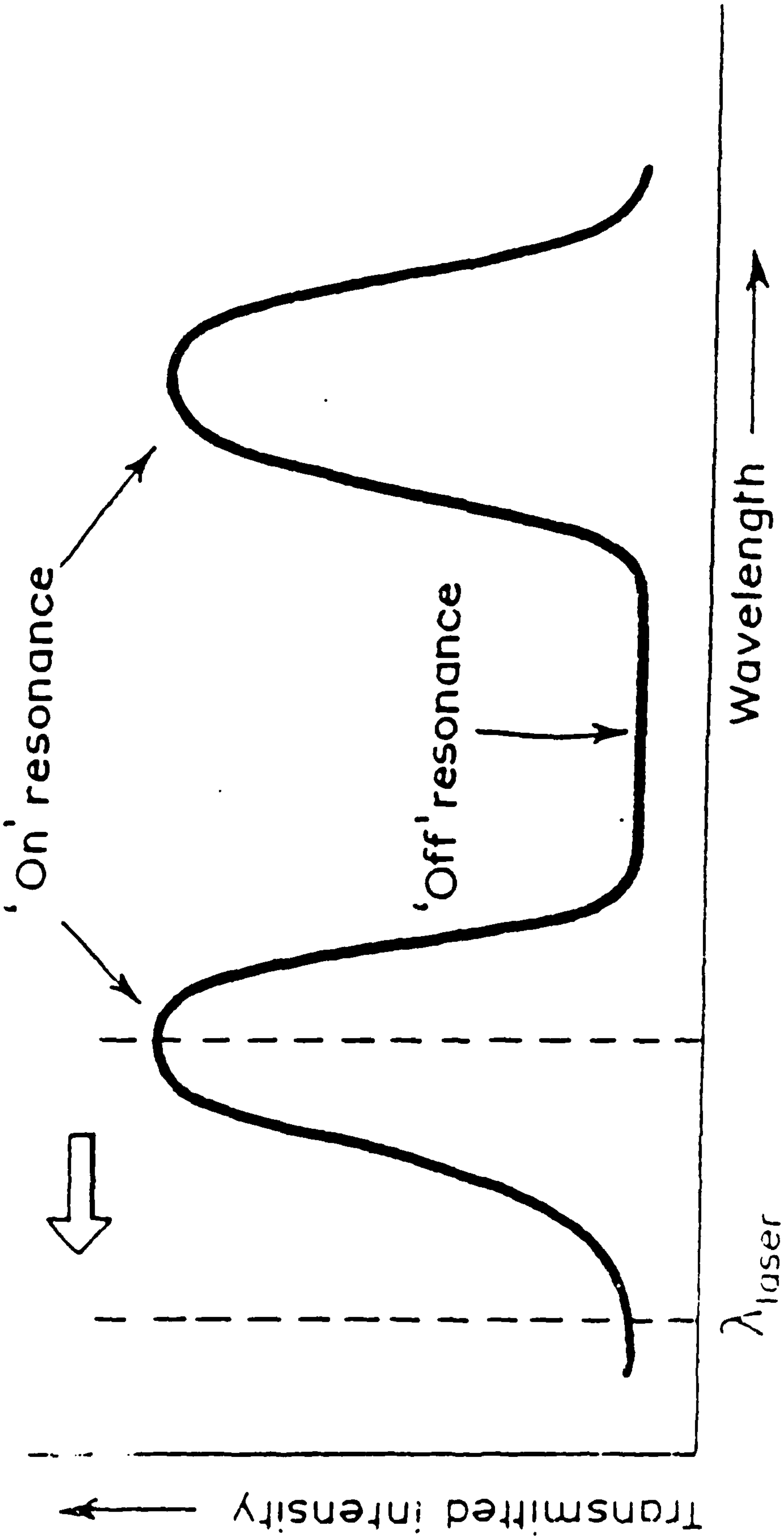


Fig. 1

Transmission characteristics of a Fabry Perot resonator.

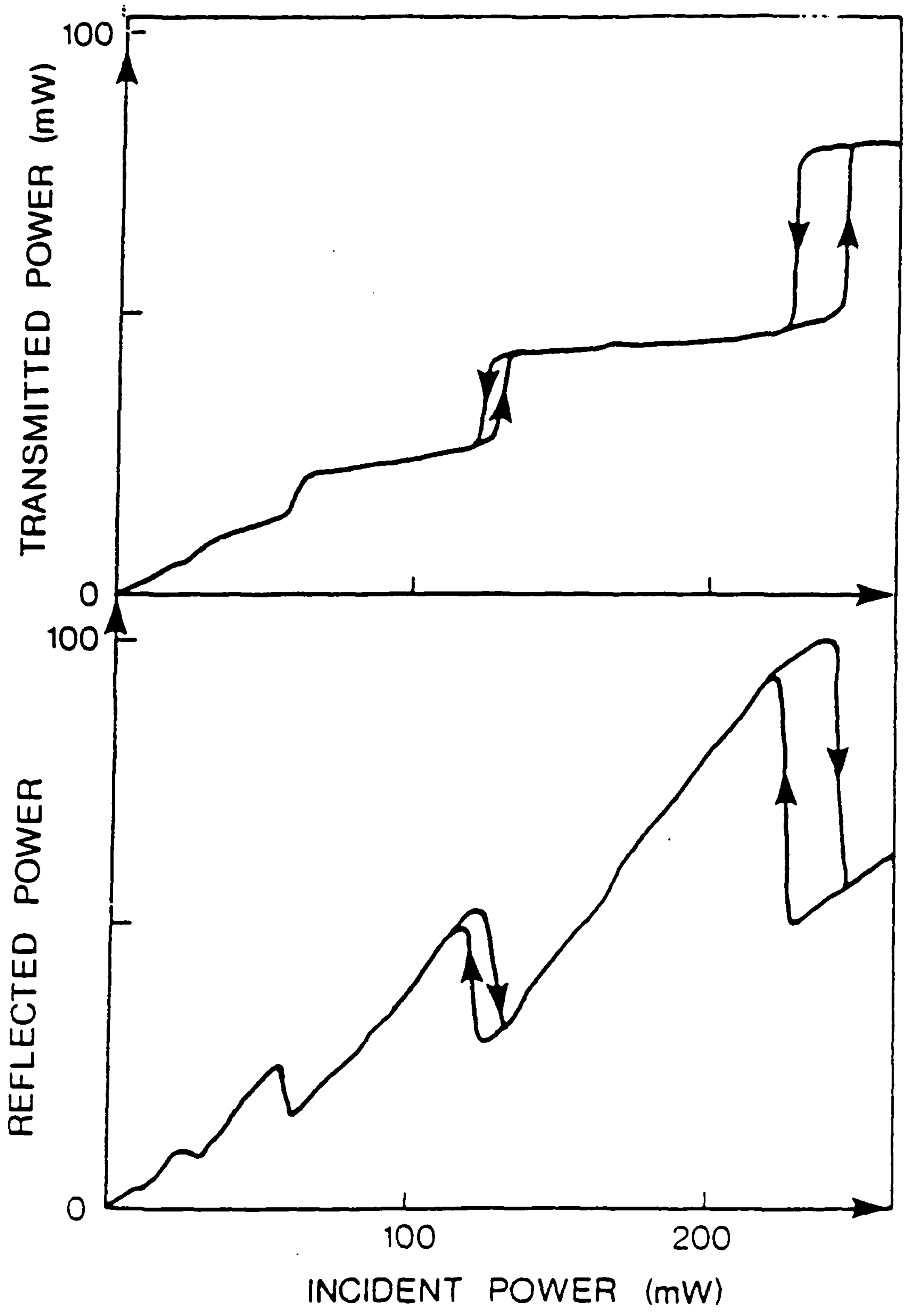


Fig. 2

Optical bistability in InSb at 5 K. Crystal thickness 560 μm with natural reflectivity (36%) faces. Incident cw CO laser wave number 1895 cm^{-1}, spot size 180 μm (after ref. 1).

simply extended the plane wave theory for a linear non-absorptive Fabry-Perot interferometer. These results qualitatively predict what is observed. In the real situation in InSb and in other materials, some absorption is required to create the refractive index change, and Gaussian laser beams are used rather than infinite plane waves.

D.A.B. Miller(9) examined the situation using a plane wave theory and incorporating linear absorption. He deduced some interesting parameters for optimising bistable devices. The most interesting from the point of view of this thesis is that for a bistable device, the most important materials parameter for a low switching intensity is not the [illegible] of n_2, it is the magnitude of the ratio n_2/α. So a weaker n_2 can be counteracted by having a lower absorption coefficient. For a given cavity, with a mirror reflectivity R, and absorption A, he found the minimum intensity for switching occurred when $1 - R = A$. Since $A = \exp(-\alpha L)$, where α is the linear absorption coefficient and L is the cavity length, a smaller n_2 means a longer cavity is required, requiring also a smaller absorption coefficient.

These results can be explained by considering that as the absorption coefficient increases the effective interaction length with the non-linear material decreases. By balancing the absorption length, the cavity length and the mirror reflectivities to provide the maximum interaction length in the non-linear material, the lowest power bistability will occur. Miller's results provide some very useful guides to possible new bistable systems, but to completely describe the experimental observations the Gaussian beam nature of the pump beam must be taken into account and the diffusion of photo-excited carriers included.

Several authors have tried to introduce a Gaussian pump beam into the problem. The introduction of spatial variations in the beam profile

results in the need for numerical solutions using enormous amounts of computer time. The most relevant work to the effects observed in InSb is that done by Firth and Wright[10]. Their results have been applied with some degree of success to experimental observations[11]. In particular the form of the spatial hysteresis seen experimentally was predicted by using their numerical model. Much theoretical work is going on into the proper treatment of transverse spatial effects in bistable systems, partially because of the interesting effects observable and partially because of the great interest in using these devices for parallel image processing.

One area in which very little work has been done is the inclusion of carrier diffusion in the problem. Since the diffusion length in InSb is several hundred microns, this is clearly going to be of some significance when trying to construct several elements near to each other on one crystal. There is still, therefore, a very large amount to be done on the InSb bistable system, before a complete understanding is obtained.

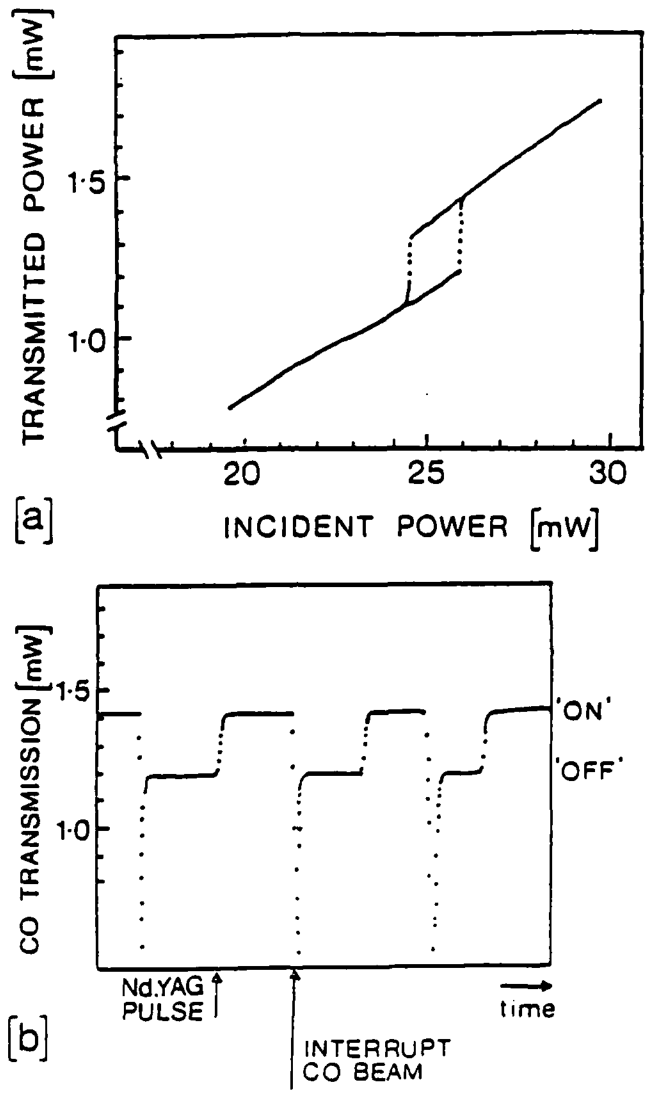
4 InSb Optically Bistable Resonator

The experimental layout used to set up the bistable resonator was the same as that used in previous experiments. The Fabry-Perot cavity consisted of a 210 μm thick InSb crystal (n-type $\sim 4 \times 10^{14}$ cm^{-3}) with natural reflectivity (R = 0.36) polished faces, mounted in a rotatable cryostat, and held at a temperature of 77 K. Radiation was provided by an Edinburgh Instruments PL3 cw CO laser operating

at 1819 cm^{-1}. The beam was focussed onto the sample using a BaF_2 lens to produce an incident beam diameter of 200 μm. This was measured using a pyroelectric detector with a 10 μm pinhole, scanned across the beam. Variation in intensity over 4 or 5 orders of magnitude while maintaining the Gaussian beam profile was obtained using a variable attenuator slide in conjunction with a spatial filter(13). The input and output powers were monitored using Laser Precision cw power meters, the outputs of which were connected to the x and y channels of a storage oscilloscope.

This system allows transmission measurements to be made very easily and quickly over several orders of magnitude of incident intensity, and has proved to be extremely useful in looking for non-linear optical effects around the bandgap in InSb(14). The sample was moved about in the laser beam, its variation in thickness being used to get the correct cavity detuning for optimum bistability(15). The input versus output power is shown for this detuning (fig. 3). As can be seen for input powers of around 25 mW two possible outputs are available for a given input. This is known as the bistable region. The lower branch of the curve is as previously discussed known as the off-resonance transmission state, and the upper branch the on-resonance state.

Using samples with PbTe/ZnS high reflectivity mirrors, bistability has been obtained using much lower intensities, but a natural uncoated sample was used here to make as simple a system as possible.



InSb Sample, t~210μm, R~36%,

Laser on 1819cm^{-1}

spot dia.~0.2mm

Fig. 3(a) Transmitted power plotted against incident power. (b) Transmission of incident cw CO laser beam at ~ 26 mW showing "on" switching caused by a single 35 ps pulse from a Nd:YAG laser. Switch off is caused by interrupting the CO holding beam.

5 Switching Dynamics

The use of this device as an optical memory is of great interest, and hence the switching speed is of great importance. The mechanisms involved in the switching are extremely complicated, due to the spatial effects of defocussing on the Gaussian input beam, the coupling between the forward and the backward field, the time taken for the refractive index change to follow the intensity change and carrier diffusion.

As has been stated previously, under the excitation conditions used here refractive index change is directly proportional to the number of photoexcited carriers. It is only in the steady state condition that $\Delta n = n_2 I$. For a change in refractive index to occur excited carriers must be created or recombine. The change in optical path length ($\Delta n \ell$) required for switching can be estimated to be in the experimental conditions used $\sim \lambda/10$ from the theory of Felber and Marburger(8).

The time taken for refractive index to increase, i.e. carriers to decay after an instantaneous change in intensity, is obviously the excited carrier recombination time, which is 100-1500 ns.
The amount of time taken for the refractive index to decrease i.e. carriers to be excited after an instantaneous increase in intensity is more complicated. This depends on the rate at which carriers can be excited, as well as on the photo-excited carrier recombination rate.

If all the carriers are created by a cw CO laser this time can be quite long 50-500 ns. The switching process will be considerably complicated by spatial and diffusion effects. The switch-up time can be decreased by using progressively higher laser powers including some means other than a CO laser to introduce the necessary photoexcited carriers. Similarly the

switch down time, dependent on the carrier recombination time, could be changed by engineering the material, say using surface or defect effects to reduce carrier lifetime.

The fundamental limit on switching is the cavity field build up time t_c, given by

$$t_c = \frac{2n_oL}{c(1-R)} \qquad 5.1$$

In the cavity used L = 210 μm, and R = 0.36, so t_c = 8 ps. This is the fundamental limit on switching speed in this device.

The experiment described in the next sections provided some information on the dynamics involved.

6 Switching of an InSb bistable resonator held with a cw 5.5 μm laser beam, using a 1.06 μm 35 ps pulse

A Nd:YAG modelocked laser was used to produce a single short (35 ps) pulse, which was incident on the active area of the sample. The experimental layout is given in figure 4.

The bistable cavity was set up so its transmission characteristic was given by figure 3(a). The input power was adjusted so it was in the off-resonance position, or lower branch of the bistable loop. The Nd:YAG laser was turned on with a 1 Hz repetition rate: neutral density filters were used to find out at what energy the cavity could be made to switch from off- to on-resonance with a single pulse. By displaying the output from the power meter on an oscilloscope with a very slow time base, it could easily

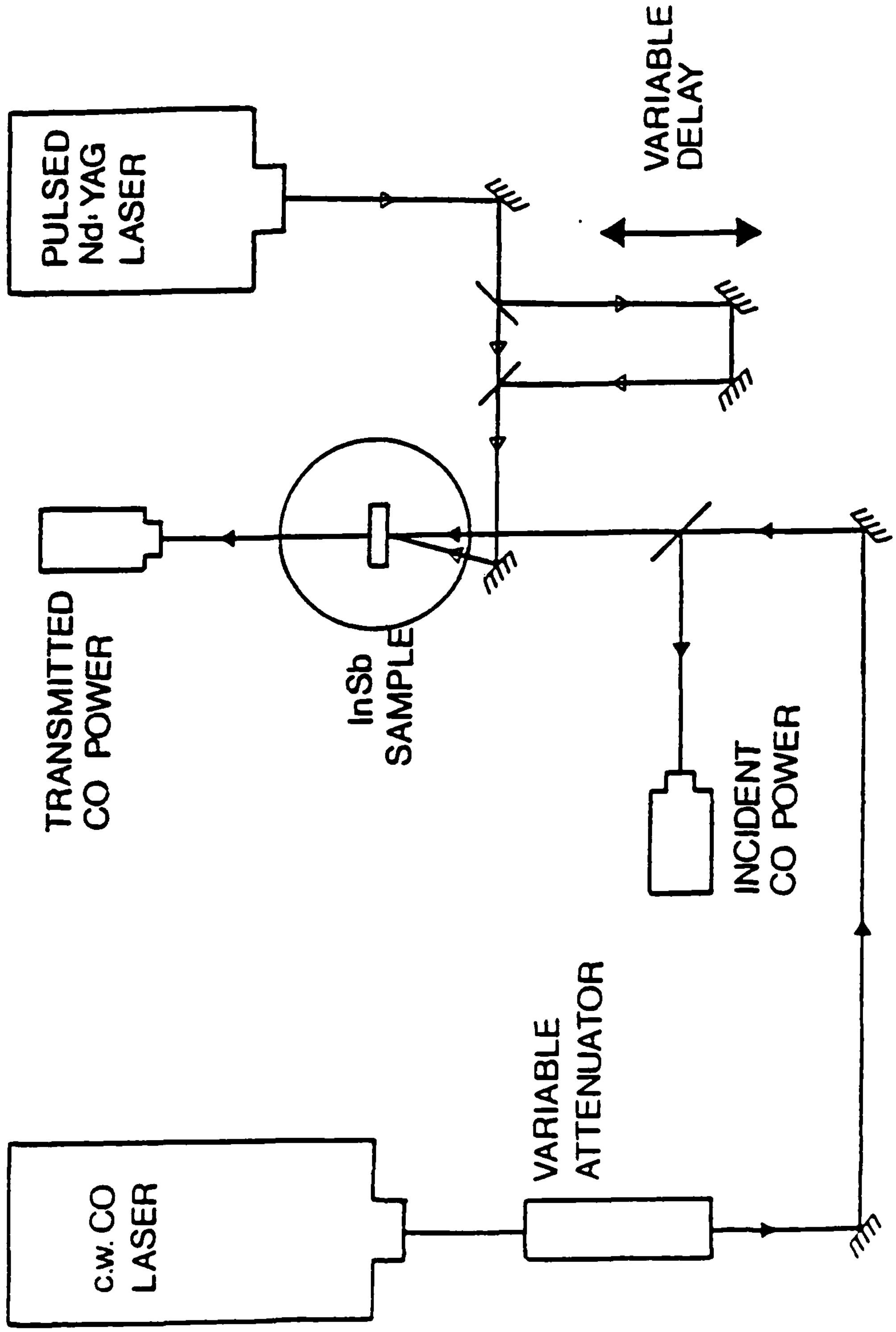


Fig. 4

Experimental apparatus for external switching and AND gate experiments on a bistable InSb cavity.

be seen when a switch takes place. The cavity was reset by blocking the incident beam and the next pulse 1 s later, switched it again. Figure 3(b) shows this happening.

The threshold energy for switching was found to be 5 nJ, incident on the active area of the sample. The exact energy was obtained by using a 5 mm radius Nd:YAG beam on the sample and working out how much was incident on the 200 μm 1/e diameter of the cw CO holding beam, which forms the bistable element. The energy measurements were done using a Laser Precision Rk 7000 pyroelectric energy meter. This was interfaced to an HP85 minicomputer for easy data collection.

The mechanism for switching was obviously non-thermal, since an increase in temperature would cause an increase in refractive index (since at 77 K an increase in temperature of InSb results in a narrowing of the bandgap) and this would not cause a switch from off to on to occur. The 1.06 μm pulse causes a decrease in refractive index and hence an increase in transmission so more CO intensity is allowed into the cavity and this holds the cavity on resonance, even when the effect of the pulse has decayed away.

The mechanism responsible for the switch on is the creation of electrons in the conduction band of the InSb sample by the Nd:YAG pulse. These can be created by three mechanisms, either by excitation from the split-off band which is 1.13 eV below the conduction band, by excitation from the heavy hole high up into the conduction band or from the light hole into the conduction band. These excited electrons only have a major effect on the refractive index at the CO holding beam frequency if they occupy states near the band edge. The electrons will thermalise rapidly down to

the bottom of the conduction band, before relaxing to the valence band. The thermalisation process will occur in < 1 ns, perhaps < 100 ps, then the electrons will take several hundred nanoseconds to relax back in to the valence band.

The electrons, while at the bottom of the conduction band, cause the refractive index to change sufficiently to change the optical path length enough to increase the cavity transmission (for the 1819 cm^{-1} holding beam) to a level where the holding beam can itself maintain a high enough carrier concentration, to keep the cavity on-resonance. The whole switching process is complicated by a number of factors, notably the Nd:YAG pulse is absorbed in the first 1 μm of the sample, because of the high absorption coefficient. Diffusion must therefore be taken into account, as well as the interband scattering, and the Gaussian beam nature of the holding beam.

The pulse energy used, 5 nJ, is equivalent to 2.7×10^{10}, 1.17 eV photons. Over the effective area of the CO beam 10^{14} photons/cm^2 are introduced. These are all absorbed in 1 μm of the sample producing a population density of $\sim 10^{18}$ cm^{-3} (assuming each incident photon produces one excited carrier). The carriers will produce an effective path length change due to their effect on the refractive index. Assuming each photon actually produces a carrier in a thermal distribution at the bottom of the valence band, σ, the refractive index change per absorbed photon, per unit volume can be given, in terms of a known function $J(x)$ [3,6,7],

$$\sigma = 0.9 \times 10^{17} \frac{1}{T} \frac{1}{(\hbar\omega)^2} J\left(\frac{\hbar\omega - E_G}{kT}\right) \text{ cm}^3 \qquad 6.1$$

where T is the temperature in degrees Celsius and the photon energy $\hbar\omega$ is given in eVs. For the experimental conditions, the laser operating at 1822 cm^{-1}, $\sim$ 2 meV below the energy gap, and the temperature 77 K, each carrier per unit volume will change the refractive index seen by the CO laser by a value $\sigma = 7 \times 10^{-19}$ cm^3, thus giving a change of refractive index $\Delta n = \sigma N \sim 0.5$ in the first 1 μm of the sample, where all the carriers are created.

To switch the cavity from completely off to completely on resonance the path length change would be $\lambda/2$ but, since the cavity is already held close to the switch-up threshold by the CO laser field, only a change in path length of $\lambda/20$ is required. This means the change in refractive index required would be $\Delta n \sim \lambda/20L = 2.7 \times 10^{-1}$. The expression 6.1 is only true for the Boltzmann regime where non-degenerate statistics can be used to describe the carrier distributions in the semiconductor, so in this case with carrier concentrations of 10^{18} cm^{-3} it is clearly not accurate. The value of σ used is therefore the upper limit. Also in calculating the carrier density, it has been assumed that each absorbed photon creates only one carrier at the bottom of the band, whereas because of the high energies to which the carriers are excited, Auger recombination may result in the excitation of more than one excited carrier per absorbed photon.

It is in fact surprising that this theoretical calculation comes so close to the experimental result. It should be noted that the short pulse may be switching the cavity on at the optimum limit of the optical field build up time of 8 ps.

The requirement for setting the switch up is that the Nd:YAG induced carriers have to stay there long enough for the CO laser to maintain the new increased carrier density itself, and so allow the resonator to maintain

itself on the upper branch of the hysteresis loop. The amount of time required to do this can be shown to be of the order τ_R, the photoexcited carrier recombination time. For an incident cw laser power of 26 mW at 1819 cm^{-1} on a 200 μm spot diameter for a 210 μm cavity length and a measured absorption coefficient of 8 cm^{-1}, 2 x 10^{21} photons/cm^3/sec are absorbed. To hold the device on the upper branch it would take ∿ 150 ns to generate enough extra excited carriers, which is comparable to the inter-band recombination time. In the time taken for this to occur the carriers induced by the Nd:YAG pulse will have diffused through a much larger volume of the sample. The effect of diffusion out of the sample will be cancelled out by diffusion of carriers into the active volume, since the entire sample has been irradiated by the Nd:YAG pulse. This will have the effect of causing the Nd:YAG induced carriers to spread throughout the sample length. In the simple model where each carrier has the same effect on the refractive index, the path length change is independent of the distribution of these induced carriers throughout the length of the sample [since $\Delta n(\ell) = \int_0^L \Delta n(\ell)d\ell$] so to first order diffusion has no effect.

Bearing in mind the number of approximations made, the experimental results agree very well with the theoretical predictions. This good agreement can be contrasted with that obtained by Starng et al.[17]. They performed a similar experiment with a pulsed dye laser operating at 750 nm to make a GaAs bistable etalon, using a saturable excitonic absorption. This etalon was then switched using a pulse from a dye laser operating at 600 nm. The energy required to cause the etalon to switch was over 100 times that calculated.

It should be possible to switch the cavity transmission up and down with the 35 ps pulse, by changing the optical length of the cavity by

greater than $\lambda/2$ and hence reaching the next interference order of the etalon. As the carriers induced by the Nd:YAG pulse decayed away, the cavity would relax back to the upper branch of the first bistable loop. We attempted to detect this transient effect, but our detection system, a Cu:Ge detector held at 4 K, with a Hewlett Packard 100 MHz-1.3 GHz amplifier and a Tektronix 7104 oscilloscope, proved to be too insensitive.

Another method was used to get some information on the time dependence of the switching.

7 Measurement of Carrier Recombination Rate using Two External Pulses

The exact mechanism for introduction of carriers into the bottom of the conduction band is not important. *All that is required for the switching* is that enough refractive index change is induced by the "externally" excited carriers for a long enough time for the cw laser to maintain a sufficiently high population to hold the cavity in the higher transmission or on-resonance state, or the device will fall back into the low transmission or off-resonance state.

By temporally separating two pulses from the Nd:YAG laser a determination of the excited carrier lifetime can be made. Whether two pulses with a fixed delay have a cumulative effect in inducing switching depends on the recombination rate of the carriers excited by the first pulse and specifically how many of these carriers remain when the second pulse arrives. The measurements were taken by adjusting the first pulse on its own to switching threshold, then adjusting the delayed pulse on its own to threshold. Both pulses were attenuated by a factor of 2

and allowed to be incident on the sample. The attenuation of the second pulse was adjusted so that both pulses together caused switching. The procedure was then carried out for several fixed delays. By plotting the log of the attenuation of the second pulse versus the delay between the two pulses, a good fit was obtained to an exponential dependence of attenuation on delay (figure 5). This fit implies that the carrier recombination occurs exponentially with a recombination time of 90 ns. Since diffusion would result in the distribution of carriers into the active volume, this should be a bulk measurement. The value is significantly less than expected and perhaps the initial carrier concentration at the front of the sample results in Auger, radiative and surface effects, which would be complicated further by diffusion.

The situation is complicated since Gaussian beam bistability, even in a medium where $n(I) = n_0 + n_2 I$ exactly, has not been explained, and the introduction of the microscopic mechanism for the non-linearity adds another level of complexity, with diffusion and recombination entering the problem.

This type of experiment can be extended to other cw holding powers to investigate the intensity dependence of the recombination time, and the energy threshold of the system. Three orders of bistability can be obtained allowing a wide range of intensities to be covered. Unfortunately this experiment is extremely hard to do. Delays corresponding to paths of over thirty metres are required which are very hard to set up.

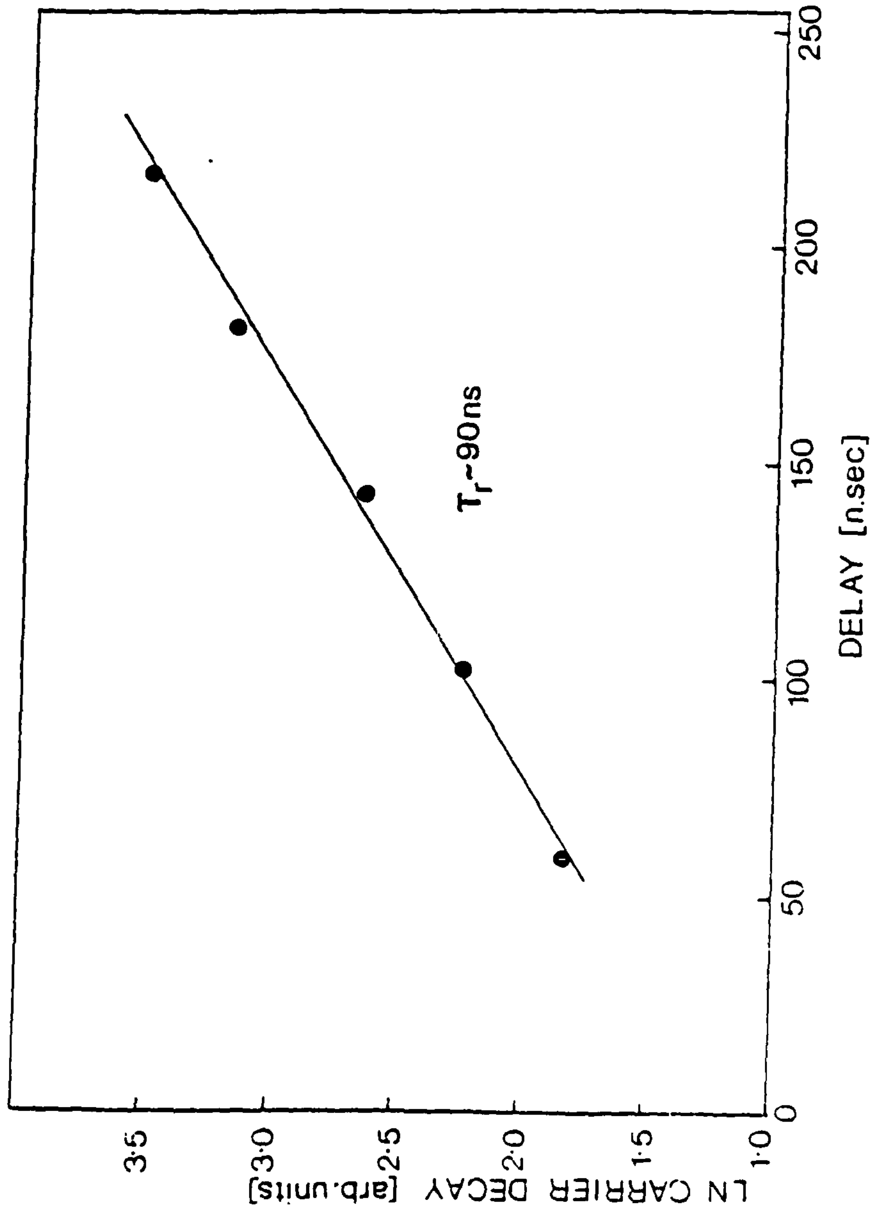


Fig. 5

Dependence of Nd:YAG induced carrier decay on optical delay between AND gate pulses. The straight line through the experimentally measured points indicates an exponential decay with a recombination time $\sim$ 90 ns.

PART 2

In attempting to extend the low power band-gap resonant effects seen in InSb at 77 K described in PART 1 to room temperatures, and to different wavelengths, a tunable laser-like source of radiation is required. In addition, an ultrashort pulse source would be desirable. The dynamics of these effects are very interesting, not only from a purely scientific point of view, but also for potential use in all optical processing systems. The region we chose to investigate was from 1.5 to 2.0 μm, with materials such as GaSb, InGaAs and InGaAsP.

The growth techniques required to fabricate devices using these materials are highly developed, and the potential use with semiconductor lasers and fibre optics was, and still is, a major motivation for future work. The photon energies 600-830 meV are midway between those used in the InSb experiment (∿ 230 meV) and the photon energies used to observe excitonic effects in GaAs (∿ 1.5 eV).

There are very few tunable laser sources in the 1.5-2.0 μm spectral region, so very little semiconductor research with lasers has been done in these materials. At the time this project was set up (1981) 1.06 μm pumped parametric oscillators and amplifiers were the only proven system. Now F-center[2] lasers look promising as tunable sources at these wavelengths although they are still at the development stage.

As a first stage in studying the nonlinearities in semiconductor materials with energy gaps in the near infrared the construction of a novel Nd:YAG pumped Lithium Niobate optical parametric amplifier has been funded by the Science and Engineering Research Council, UK. A mode-locked Nd:YAG laser, producing one single pulse approximately 35 ps long, with energies up to 10mj, was used to optically pump a 5cm long lithium niobate crystal. The system has been shown to be a useful sources of optical pulses of up to 50μj in the 1.5 to 2.12 μm region.

The unique design produces a relatively narrow bandwidth (less than 6cm^{-1}), with no long-term variation in wavelength, using a single crystal. This source is ideal for our work in extending the low power non-linear effect, found in InSb near 5 m at both 4K and 77K, to other semiconductor materials.

The pump laser, a JK Lasers Nd:YAG system, produces single 35ps pulses at 1.06µm of energies up to 10mj and repetition rates of up to 10 Hz. Our lithium niobate crystals are both 5 cm long cut with their optic axis at 45° to the front surface of the crystal. Both crystals are broad band A.R. coated for 1.06µm and 1.6 to 2.0µm. The crystal on which all the earlier work was done was a 2cm diameter crystal on loan from Los Alamos National Laboratories, and the later work was done on a 1cm diameter crystal purchased from J.K. Lasers.

Both crystals perform similarly with the second not a poorer beam profile due to optical imperfections in the crystal.

The bandwidth of the output is determined by the phase matching conditions, which in turn depend on the temperature and on the exact angle between the beam propagation and the optic axis of the crystal. The bandwidth of the parametric output is several hundred wave numbers, clearly too high for a detailed study of a semiconductor band edge such as that done in InSb.

However, when a narrow bandwidth pulse is propagated through the crystal with a YAG pulse, if the phase-matching conditions are appropriate, this narrow-band pulse is amplified maintaining its narrow bandwidth. Using this feature, the bandwidth of the system was $6cm^{-1}$ from 1.5 μm to 2.12μm. Output energies of 40 μj were easily obtained for a 2.5mj input throughout the wavelength range, in pulse 35ps.

CONCLUSIONS

a) This experiment has shown that an InSb bistable resonator held with a 5.3 μm laser beam can be switched using a 35ps, 5 nJ optical pulse at 1.06 μm. It acts as a test for our previously developed model of the refractive non-linearity seen in InSb at 77K. The agreement between experiment and theory is very good considering the number of uncertainties involved.

It is important here to emphasise the potential significance of this result for device application of this non-linearity. The bistable resonator has acted as an optical memory triggered by a 35ps pulse at a different wavelength, and in the two pulse experiment as an optical AND gate. In this case the inputs were provided by an ultrashort pulse from a Nd:YAG laser, but the wavelength or coherence of the "external" pulse is immaterial as long as it results in the creation of photoexcited carriers. Indeed, switching has been demonstrated at Heriot-Watt using an electronic camera flashgun [18]. Much research is going on in this area of incoherent-to-coherent conversion.

b) We have a picosecond radiation source tunable from 1.5 to 2.1μm. Pulses less than 35ps long can be produced at repetition rates of up to 10Hz. Energies of between 5 and 20μJ are available across the tuning range. The beam divergence is 25 mrad. The output is somewhat variable due to the erratic pump laser output, but this has been overcome by using a minicomputer to collect and process the data.

The utility of this system for the investigation of carrier dynamics in semiconductors will be the subject of our continuing work, particularly in the compounds $In_{1-x}Ga_xAs$ and $In_{1-x}Ga_xAs_yP_{1-y}$.

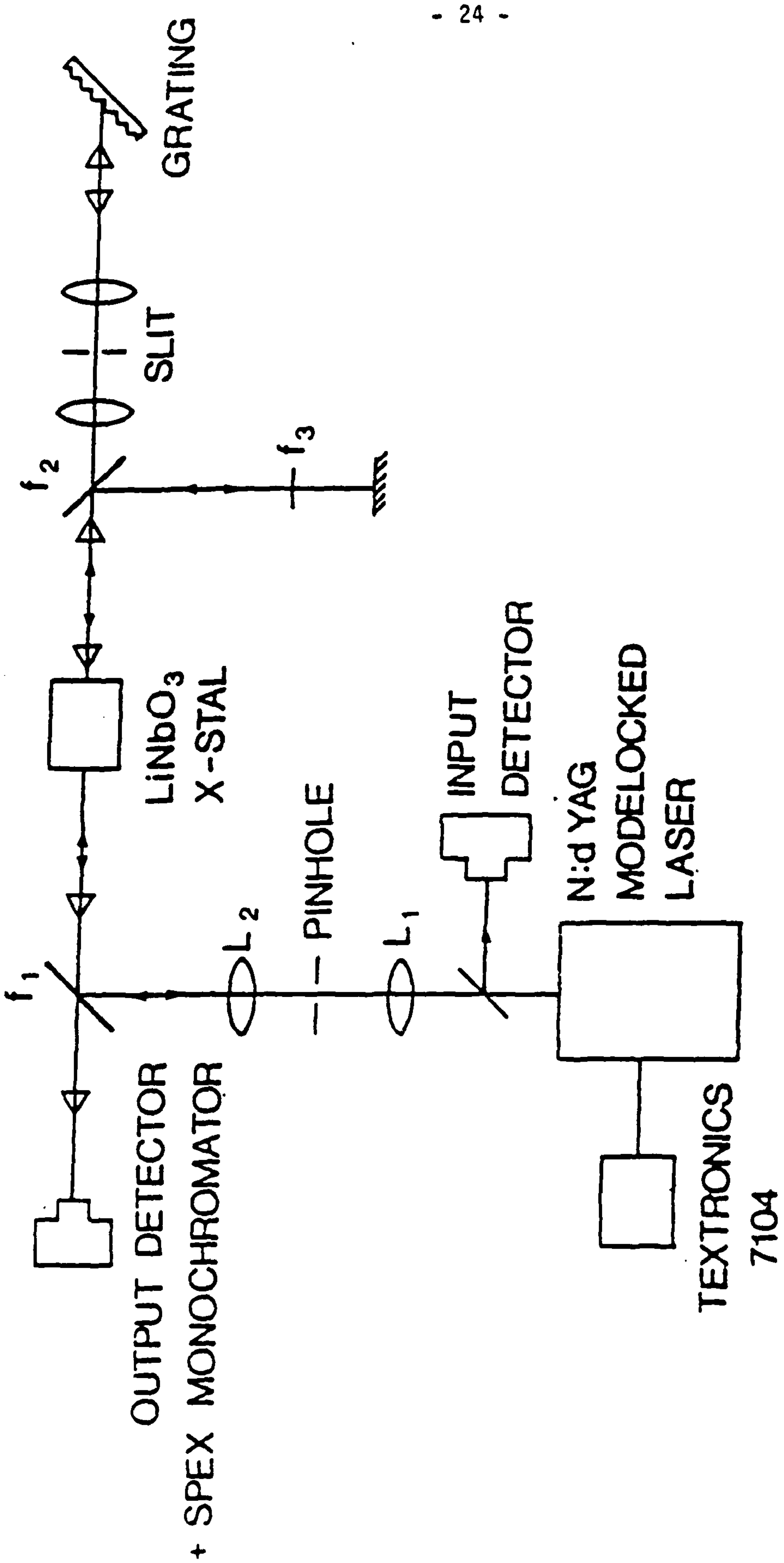


Fig. 6 Experimental layout of the OPA.

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